buildings

Case Report

Performance of Epoxy-Injection and Microorganism-Based Crack-Healing Techniques on Cracked Flexural Members

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Abstract: Reinforced concrete (RC) members are designed to crack and the crack width usually remains within the service limit; however, these micro-cracks make structures susceptible to the infiltration of aggressive substances, especially near the coastline. Thus, the healing of these cracks is necessary before they further widen and spread. This study focused on the development and application of a crack-healing solution using microorganisms of the class bacillus; healing was observed through a crack-sensing camera. The aim was to regain the load-carrying capacity of the concrete member to meet the serviceability limit state requirements after healing the crack. The performance of the crack-healing solution was compared with the epoxy-injection method. Five full-scale RC beams of 100 × 200 × 1800 mm in dimension were cast using concrete designed with a cylindrical compressive strength of 21 MPa. After curing for up to 28 days, the beam specimens were tested and subjected to four-point bending to produce a flexural crack of width 1–3 mm. One of the beams was treated to fill the crack by injecting epoxy, while the three other similar beams were treated using a crack-healing solution consisting of bacteria (*Bacillus subtilis*), nutrient (calcium nitrate), and transporting agents. The healing solution was applied directly to the opened crack with silica gel and with cement slurry in three similar beams cracked under flexural load. The cracks in the beam treated with the crack-healing solution were sealed and kept moist for a further 14 days. After curing, all of the beams including the control (without treatment) were tested again and were subjected to four-point bending until failure to observe the effect of the crack repairs on the flexural response. It was observed that both systems were equally good at enhancing the serviceability limit state and improving the load-carrying capacity.

Keywords: flexure; crack-healing; epoxy; microorganism; silica gel

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1. Introduction

The yearly repair and maintenance rate for reinforced concrete highway bridges due to the corrosion of reinforcement is a major financial burden for developed countries. Therefore, maintenance and repair costs remain a vital concern for management and researchers, as the cost of crack detection and repair is massive [1,2]; this is why reinforced concrete structures face enormous maintenance costs during service. In reinforced concrete structures, the two major causes of deterioration are the self-deterioration of the concrete and the corrosion of the steel reinforcement [2]. Cracking in concrete plays a dynamic part in reinforcement corrosion by creating contact between the water and reinforcing steel, which generally comprises dissolved ions. Recent research [2] stated that hairline cracks (0.3 mm) [3] also affect the corrosion phenomenon. Thus, cracking is one of the chief hurdles to the progress of modern concrete technologies [4]. The risks associated with cracks ruthlessly restrict the performance of cement-based materials and the functionality of concrete structures. To overcome the limitations of cracks on concrete durability and service life, researchers around the world have developed a variety of crack self-healing technologies [4–7]. Qian et al. [4] explored the construction technologies of microbial self-healing concrete (SHC) through engineering practice and observed that the spray-dried fermented bacteria technique exhibited abundant potential for the development of powder and capsule-based microbial healing agents for concrete. In comparison with liquid-based healing agents, this technique is more appropriate in terms of production, transportation, storage, and utilization. For effective self-healing effects, it is essential to consider the necessary curing measures to keep the cracks wet and supply nutrients to the bacteria. To quantitatively depict the self-healing competence in construction sites, the degree of self-healing can be evaluated by observing the changes in ultrasonic wave speed and waveform, which is an effective non-destructive technique. In recent time, the monitoring of crack in RC members are greatly improved through There is improvement in crack monitoring through techniques such as fibre-optic sensing of cracks by Digital image correlation [8] and crack-sensing cameras [9] which make enable measuring the crack width accurately (more than 95%) [10] and monitoring the healing of crack.

Comparing the crack self-healing with conventional epoxy-injection technology, it is a general assumption that epoxy injection is an economical technique for repairing dead cracks (cracks of constant width), which are generally observed on concrete walls, columns, slabs, etc. According to ACI 546R-96 [11], epoxy resins generally have very excellent bonding and durability characteristics. Ahmadi et al. [12] recently reported an investigation on the repair of tension cracks in RC panels subjected to direct tensile loading and hydrostatic pressure by utilizing high-performance materials such as high-strength epoxy, glass fiber reinforced polymer (GFRP) laminate, and engineered cementitious composite made from slag and fly ash. The findings of this study were primarily associated with the water tightness and the prime conclusion of this study was that epoxy injection can be used as an indigenous repair solution for RC cracked sections, while cracks may appear at new places under the same loading level. This results in a repetitive cycle of epoxy injection influencing the repair efficiency. A recent review [13] on the efficiency of the epoxy-injection technique for repairing normal and high-strength concrete beams stated that epoxy injection is an effective approach to restore the original structural integrity and stiffness if adequate repairing measures are adopted. The use of low-viscosity epoxy was preferred due to its easy and deep penetration into the cracked zone, which efficiently restored strength and, conversely, less deep beams exhibited a greater improvement. Moreover, the amount of drilled holes for injection directly affected the results, and fewer holes improved the strength significantly. However, one should keep in mind that this method is not applicable where there is continuous moisture present [14]. In addition, epoxy-based fillers or rubber-based water repellents are also not suitable due to their short-term efficiency and negative impact on the environment [15]. Therefore, an alternate method in which bacterially induced calcium carbonate precipitation has been proposed, and was successfully applied on the cracked surface of a limestone monument [16]. In this technique, urea was hydrolysed by enzymes in a calcium-rich environment, producing calcium carbonate, as the hydrolysis of urea itself produces a large amount of nitrogen gas, which is not environmentally friendly. The alternative is to use bacterially induced calcite precipitation through the metabolic conversion of calcium lactate instead of urea hydrolysis, which has been successfully applied on self-healing concrete [17]. However, the question is which type of bacteria is suitable as a healing agent? The answer lies in the literature, as two major types of bacteria that can be used as healing agents, namely ureolytic and non-aromatic, are being investigated [18].

Urea-positive bacteria include *Bacillus sphaericus* and *Bacillus pasteurii*, which are involved in forming biominerals. When urea hydrolysis occurs in $CaCO_3$ precipitates, a solid crystalline material is created. The enzyme urease is used to regulate the biological process of hydrolysis of urea, which produces carbonate ions without producing protons. Dick et al. [19] developed bacterial concrete using a particular type of bacteria that can decompose urea. Such ureolytic-based bacteria induced in the mortars and concrete during the mixing phase produced minerals that rapidly sealed freshly formed cracks. This follows the mechanism in which bacteria in the presence of urea and bacterial enzyme (urease) rapidly start the hydrolysis of urea to produce ammonium and carbonate with the increase in pH level. Calcium ions are further converted into $CaCO_3$ once the super-saturation of carbonate ions is achieved. The underlying chemical reaction [20] is shown in Equations (1) and (2):

$$CO(NH_2)_2 + 2H_2O \ \overrightarrow{urease} \ 2NH_4 + CO_3^{-2} \tag{1}$$

$$Ca^{+2} + CO_3^{-2} \ \rightarrow CaCO_3 \tag{2}$$

Such urea-based precipitation has shown effective self-healing, but urea has limited long-term stability in an alkaline environment. Moreover, the urea-based mechanism also produces ammonia [21], which damages the environment and concrete.

Chitambar et al. [22] used a solution of *Bacillus subtilis* and *Bacillus sphaericus* along with calcium lactate as an organic precursor, while Lucas et al. [23] incorporated Genus Bacillus with a combination of calcium lactate and yeast extract as precursors to carry out the most effective two-component healing agent. According to Dhami et al. [16], numerous types of *Bacillus subtilis* were selected, while only one type among them, *Bacillus subtilis* M9 (extracted from the milk) from the whole study showed potential for use.

The healing of cracks is possible with cement-based materials, depending on the availability of portlandite in the matrix. The healing process, its capacity characterization [24], and the modeling of cracks closing have been reported and reviewed extensively [25]. However, limited literature is available on microorganism-based self-healing in concrete. The idea of self-healing concrete is limited to new construction only; therefore, it is necessary to develop a biological repair system for the repair of existing concrete structures. A spray was developed to assess the performance of this system and was tested on rigid pavements; it was found to be promising [15,18]. Therefore, this study focuses on the development of a crack-healing solution and its application on RC beams as a repair system. A self-healing solution was developed using strains of bacteria *Bacillus subtilis* mixed with a calcium nitrate solution. The solution was applied to the cracks of RC beams using varying techniques and the performance under flexural action was compared with a similar RC beam repaired using the epoxy-injection method. A crack-sensing camera was employed to observe the healing of the cracks. The aim was to regain the member load-carrying capacity and achieve the serviceability limit state after the healing of the crack. The spray is an innovative approach that can lead to state-of-the-art repair techniques suitable for new and existing structures.

2. Experimental Program

2.1. Material Properties and Mix Proportion

ASTM Type I ordinary Portland cement (OPC) [26] was used to prepare the concrete. In all of the concrete mixes, the maximum size of the coarse aggregates was 20 mm. River sand smaller than 4.75 mm with a fineness modulus of 3.55 was used as the fine aggregate. BASF-Master-Rheobuild-Naphthalene-Sulphonate-based high range water reducing admixture (HRWRA) of 1% of the total weight of cement was also added to obtain the desired workability. A water/binder ratio of 0.45 was used in all of the mixes. Two types of deformed steel bars of grade 60 with diameters of 10 mm and 12 mm (labelled as Ø10 and Ø12) were used as the top and bottom reinforcements of the beams. The complete response of steel bars under tensile load in a Universal Testing Machine (UTM) is shown in Figure 1. The load and deformation were obtained through a data logger attached with UTM and with KYOWA Transducers DT-A. The yield strengths for the 10 and 12 mm diameter bars were found to be 540 MPa and 560 MPa, respectively, and the ultimate strengths were observed to be 677 MPa and 681 MPa, respectively. Likewise, the yield strains for the 10 mm and 12 mm diameter bars were calculated as 0.0027 (for yield strength = 540 MPa) and 0.0028 (for yield strength = 560 MPa), respectively, using a standard elastic modulus value of steel as 200 GPa.

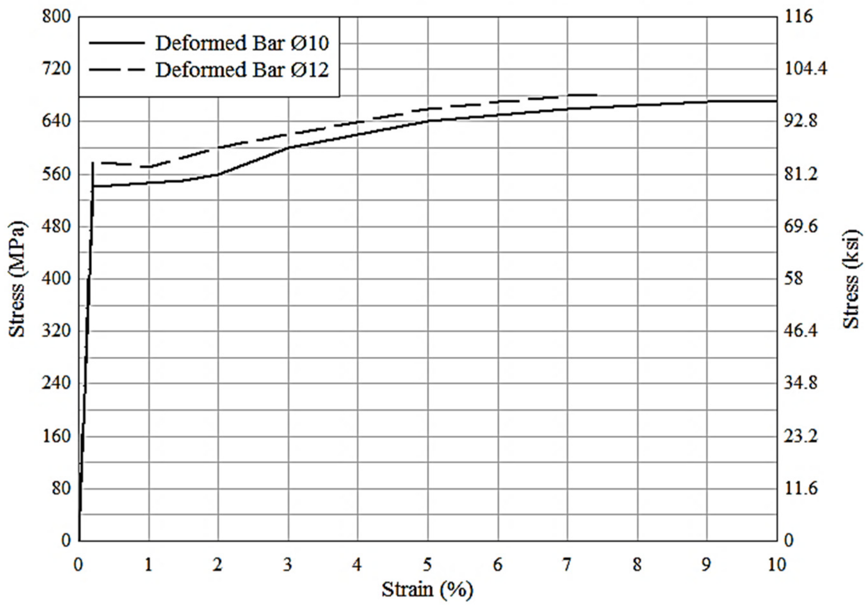

Figure 1. Tensile stress—strain response of the steel reinforcing bars.

The mix proportion (refer to Table 1) was based on ACI 318R-05 [27] and the proportion of HRWRA was set after several trials to achieve the required workability.

Table 1. Mix proportion of concrete.

Cement (kg/m^3)	Fine Aggregates (kg/m^3)	Coarse Aggregates (kg/m^3)	Viscosity Modifying Agent (VMA) (%) *	Water Cement (W/C) Ratio
329	660	1225	1.0	0.6

* VMA was added by % weight of Cement.

2.2. Mixing Casting and Specimens Sizes

The mix was prepared using a 100 L capacity pan mixer, as per the recommendations of ASTM C192/C192M [28]. The concrete had a target cylinder compressive strength of (21 $\pm$ 2) MPa at 7 days, which was verified by casting cylinders of 150 mm diameter and 300 mm height. The cylinders were tested after 7 days of curing using a compression testing machine. The average compressive strength of the concrete was found to be 19.68 MPa. The achieved average compressive strength was within the variation of 2 MPa of the targeted strength. A slump test was also conducted to check the workability of the mix. The mix was poured into the Abram cone in three layers, tamping 25 times in each layer. The Abram cone was carefully lifted and the slump was found to be 50.8 mm.

A total of three RC beams with a total length of 1800 mm and cross-sectional dimensions of 100 mm $\times$ 200 mm were cast. All beams were designed identically in flexure, as per ACI 318R-05 [27] provisions. The reinforcement detail of the beams is shown in Figure 2. For testing, the supports were adjusted such that the testing span for all beams was 1650 mm with a fixed shear span to depth $\left(\frac{a}{d}\right)$ ratio of 3.4. Two-point loads were applied at the top of the beam at $L/3$ distance, which was 550 mm. In order to measure the deflection, a KYOWA Transducer DT-A was placed at the beam bottom and touched the bottom face at middle span and at the location of point load of the beam. All of the beams were tested in displacement control mode with a displacement rate of 0.01 mm/s.

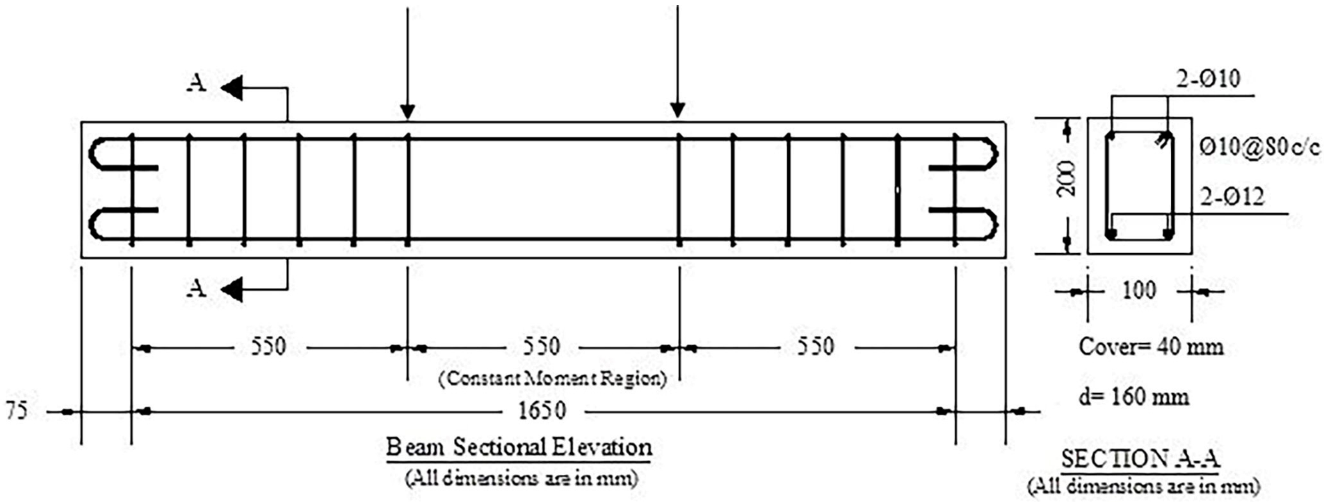

Figure 2. Reinforcement Detail of All Beams for Flexural Mode of Failure.

2.3. Development of the Crack-Healing Solution

The development of a crack-healing solution involves the culturing of bacteria, and then the preparation of broth media of desired cell concentration. The crack-healing solution consisted of two separate solutions i.e., broth medium of *Bacillus subtilis* and glucose. The crack-healing solution having bacteria was prepared following standard procedures into four parts as follows:

2.3.1. Sterilizing

The apparatus and solutions to be used were firstly sterilized by placing them in an autoclave for 1 h at 115 °C to eliminate any other bacterial species before the experiment.

2.3.2. Medium

The culture of *Bacillus subtilis* was obtained locally on a nutrient agar plate. The standard concentration for the solution was 28 g/1000 mL. A 0.4 g/50 mL broth solution was prepared by adding 60 mg/10 mL glucose as a source of carbon for bacterial growth. The nutrient agar and nutrient broth were sterilized at 115 °C for 1 h in an autoclave to eliminate any contamination. The solutions were left to cool at room temperature. The nutrient broth was preserved in a refrigerator while the nutrient agar formed a gel. Both mediums were maintained for 24 h to check whether there was any accidental contamination. The gel was heated in a microwave oven to melt it and was poured into the sterilized Petri dish carefully near to a flame to avoid any contamination. Every biological medium transfer was conducted close to a flame to avoid contamination of the sample. The Petri dish was again left for 24 h to check for any contamination.

2.3.3. Culturing

The bacterial colony was moved to the freshly developed agar medium. A wire scrapper was created red hot over a flame (to assassinate bacteria), cooled, and shifted slowly over the colony for growth on the wire. It was then moved and spread slowly over the freshly developed agar medium to transport the bacteria into the stock medium. All these processes took place close to a flame. The agar plate was left for 24 h to check for contamination. As there was no contamination of other species, the fresh cultures were ready to use. A small quantity of the bacterial colony was scraped using a wire scrapper and mixed in the broth close to a flame. The broth medium was also left for 24 h to check for contamination. The composition of the broth medium is shown in Table 2. The complete process is shown in Figure 3.

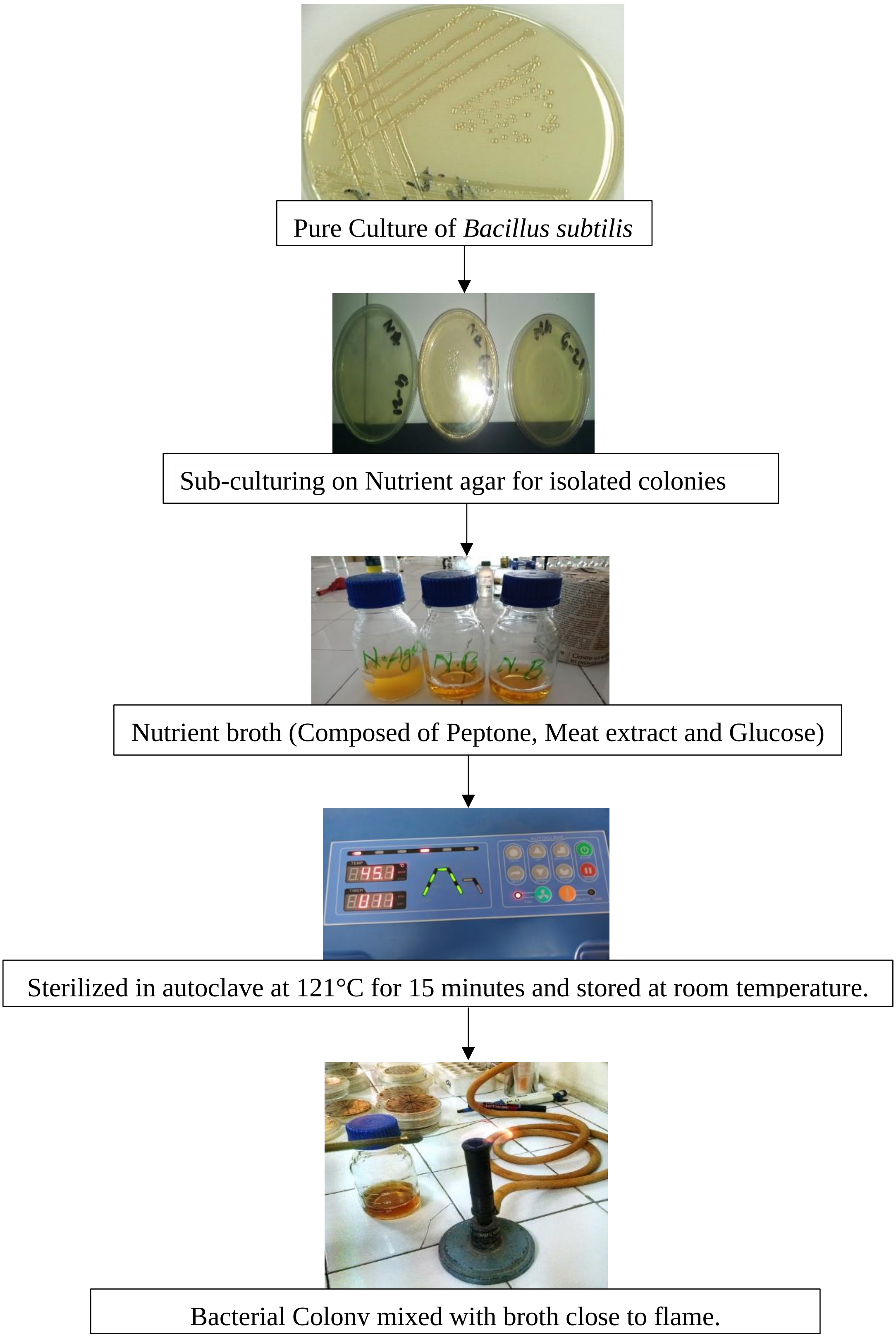

Figure 3. Complete process for the preparation of the healing solution.

Table 2. Composition of the broth medium.

Compound	Composition
Peptone 5.0 from Meat	5 g/L
$CaCl_2$	10 g/L
NaCl	5 g/L
Yeast extract	3 g/L
Meat extract	3.05 g/L

2.3.4. Balancing

The fresh broth medium consisted of bacterial species with higher concentrations than desired. A sample from the solution was tested using a spectrophotometer to check the absorbance. The bacterial species concentration was proportional to the absorbance. The wavelength was kept at 625 nm; it was found out that absorbance was in the range of 0.35–0.39, which indicated 9×10^8 cells/mL. Sterilization was conducted in autoclave culture of *Bacillus subtilis* nutrient broth (composed of peptone, meat extract, and glucose) nutrient agar sterilized at 115 °C for 1 h and then refrigerated for 24 h. Sterilized was conducted at 115 °C for 1 h and left for 24 h. The culture was prepared on nutrient agar bacterial colony mixed with broth, close to the flame standard concentration, and is shown in Table 3. The crack-healing solution prepared consisted of two separate solutions, one was a broth medium of *Bacillus subtilis* and the other was glucose.

Table 3. Standard concentration of the bacterial species (cells/mL).

Absorbance at 625 nm	Bacterial Cells/mL
0.08–0.10	1.5×10^8
0.14–0.17	3×10^8
0.27–0.31	6×10^8
0.38–0.42	9×10^8
0.51–0.55	12×10^8
0.67–0.70	15×10^8
0.74–0.77	18×10^8

The bacterial concentration used in this study was 1×10^5 cells/mL. Therefore, the volume of the solution was adjusted through dilution and the required volume was calculated using Equation (3).

$$M_1V_1 = M_2V_2 \tag{3}$$

where,

M_1—Initial concentration of bacteria in broth (9×10^8 cell/mL)
M_2—Final concentration of bacteria in broth (1×10^5 cell/mL)
V_1—Volume of solution of M_1 in mL
V_2—Final volume of solution used in the test (60 mL)

By applying Equation (3),

$$(9 \times 10^8) \times V_1 = (1 \times 10^5) \times 60$$

$$V_1 = 6.67 \times 10^{-3} \text{ mL}$$

The volume required to balance the liquid solution to a concentration of 1×10^5 cells/mL was approximately 7 µL. The volume was extracted in a micro-pipette and mixed in the basic broth medium free from any species, and then the solution was ready for testing.

2.4. Testing Setup

All of the beams were intended to fail under four-point bending conditions. One of the beams did not receive an application of crack repair and was named "control". Three of the remaining four beams were tested until the appearance of a crack 0.3–0.5 mm in width formed, and were then treated with the crack-healing solution (named beams "TCHS"); meanwhile, the remaining beam was also tested until the appearance of a crack 0.3–0.5 mm in width, and was then treated with epoxy injection (named as Beam "TEIM"). The specimens were tested under four-point bending loading to develop a pure flexure region in the mid-third of the span, as shown in Figure 4. All specimens were loaded statically to produce micro-cracks of 0.3–0.5 mm width. The crack width was monitored using a crack-sensing camera, which is hand-held device and requires no setup. Beams marked as TCHS and TEIM were then repaired using the crack-healing solution and epoxy injection, respectively, as discussed in the following section. The specimens were left to heal for 28 days and then tested until failure under four-point bending loading.

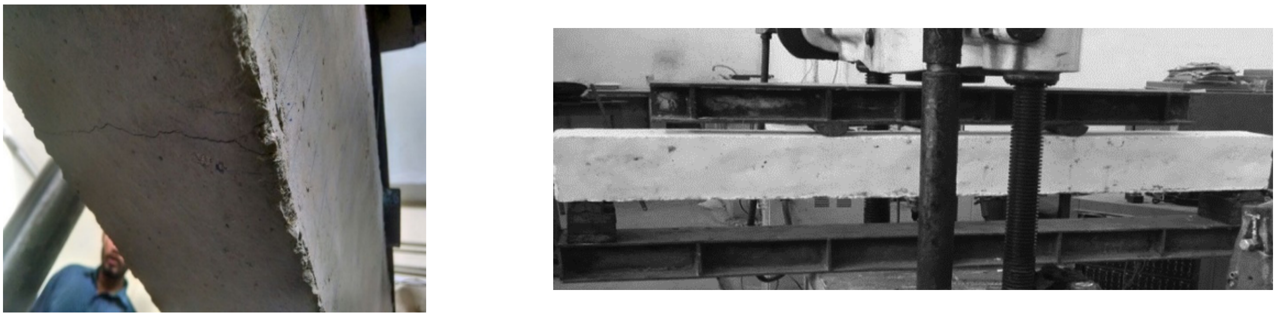

Figure 4. Testing Setup of Beams under Four-point bending Loading and Crack Appearance.

2.5. Healing of Beams

The crack-healing solution and epoxy injection were applied to the cracked sections of the beams, and they were left to cure. The details of both of these techniques are as followed:

2.5.1. Application of Crack-Healing Solution on Beam "TCHS-1"

On the first cracked beam, the formerly prepared crack-healing solution (mixture of broth of *Bacillus subtilis* and calcium nitrate) was applied directly, as shown in Figure 5. It was injected into the cracks and then the whole layer of cracks was covered with plastic tape. The specimen was then left for 28 days so that bacteria growth and crack-healing process could take place. The beam was exposed to an open environment. The temperature and relative humidity were observed during the period, ranging 35–40 °C and 60–75%, respectively.

Figure 5. Crack-healing solution application on Beam "TCHS-1".

2.5.2. Application of Silica Gel Plus Crack-Healing Solution on Beam "TCHS-2"

This beam was treated with a mixture of sodium silicate gel and crack-healing solution, which itself contained a mixture of broth medium of *Bacillus subtilis* and calcium nitrate, as shown in Figure 6. First, all the cracks were cleaned with water and dried for half an hour. The gel was then applied to the cracks and after some time (about 20 min) the gel hardened. This beam was left for 28 days so that bacterial growth within the gel took place and the crack-healing process occurred.

(**a**) Silica Gel (**b**) Mixing of Gel and Solution (**c**) Final Solution Mixture

Figure 6. Formation of the silica gel plus crack-healing solution for application on Beam "TCHS-2".

2.5.3. Application of Crack-Healing Solution with Cement Slurry on Beam "TCHS-3"

On this beam, the crack-healing solution mixed in a cement slurry was applied to the cracks (refer to Figure 7) and was left for 28 days to cure.

Figure 7. Application of Crack-Healing Solution with Cement Slurry on Beam "TCHS-3".

2.5.4. Application of Epoxy-Injection Method on Beam "TEIM"

Beam TEIM was treated using BASF epoxy injection. The two-component system based on low-viscosity epoxy resins was ideal for sealing static cracks for widths greater than 100 microns but no more than 9 mm. The epoxy was prepared by mixing hardener and base resin thoroughly until the liquid became clear. The physical and chemical properties of the material are shown in Table 4.

Table 4. Physical and chemical properties of epoxy.

Color	**Clear**
Specific gravity of mixed material (ASTM D1475) [29]	1.05 kg/L
Viscosity (ASTM D2196) [30]	204 MPa·s
Service temp. range	−20 °C to +60 °C
Compressive strength (ASTM D695) [31]	>70 N/mm^2 at 7 days
Flexural strength (DIN EN ISO 178) [32]	>70 N/mm^2 at 7 days

The beam was prepared for treatment by sealing the cracks and attaching injector packers at different locations of cracks (refer to Figure 8). The epoxy was pressurized into the packers. The epoxy was highly penetrative and cured within a few minutes to form a permanent and rigid seal against the ingress of corrosive substances.

Figure 8. BASF epoxy resin application on Beam "TEIM".

3. Results and Discussion

3.1. Control Beam

Figure 9 shows the load−deflection response of the control beam. There was an almost straight-line response until the appearance of cracks on the surface of the beams, causing the load−deflection to start curving. However, the load kept increasing until the full load-carrying capacity of about 65 kN was attained, after which the steel began to yield, followed by a gradual descending branch where the load continuously decreased, while a substantial increase in deflection was observed.

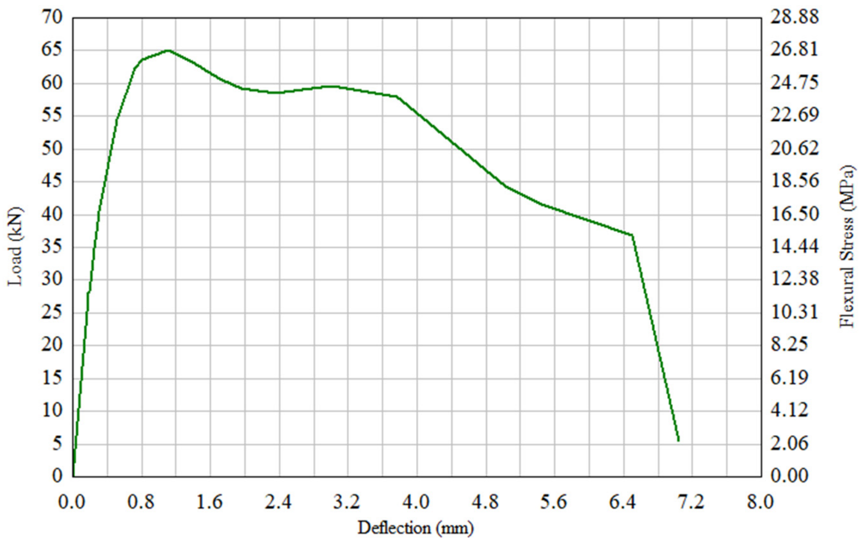

Figure 9. Load−deflection response of the control beam.

The remaining four beams were tested twice. First, they were tested until the appearance of cracks with widths ranging 0.3–0.5 mm, as also mentioned in the preceding section. After testing, each beam was strengthened using the technique mentioned in the preceding section and then cured. After the completion of curing, the beams were tested until failure. The details of the test results for these beams are as follows.

3.2. Beam "TCHS-1"

Before the application of the healing technique, Beam TCHS-1 was tested until a crack width of 0.3 mm of visible crack. A peak load of 64.54 kN was attained at about 1.28 mm deflection (refer to Figure 10). The beam was treated through the application of a crack-healing solution and was cured until the designated period. After treatment, the beam was tested again, as shown in Figure 10. The ascending branch was found to be have a lesser slope, pertaining to the drop in stiffness after healing. A peak load of 57.35 kN was obtained, which was 11% less than the load before healing. This could be due to the insufficient availability of moisture as the beam was cured in an open environment with humidity less than 50%, during the summer season. However, the descending branch was quite smooth and followed the traditional RC beam response. Figure 11 shows the healing effect of the crack-healing solution on the crack that appeared on Beam TCHS-1 with a width of 0.3 mm. Although the crack was filled with the precipitation of $CaCO_3$ due to *Bacillus subtilis* growth and metabolic activity, the healing was not sufficient as the same crack opened during re-testing of the beam.

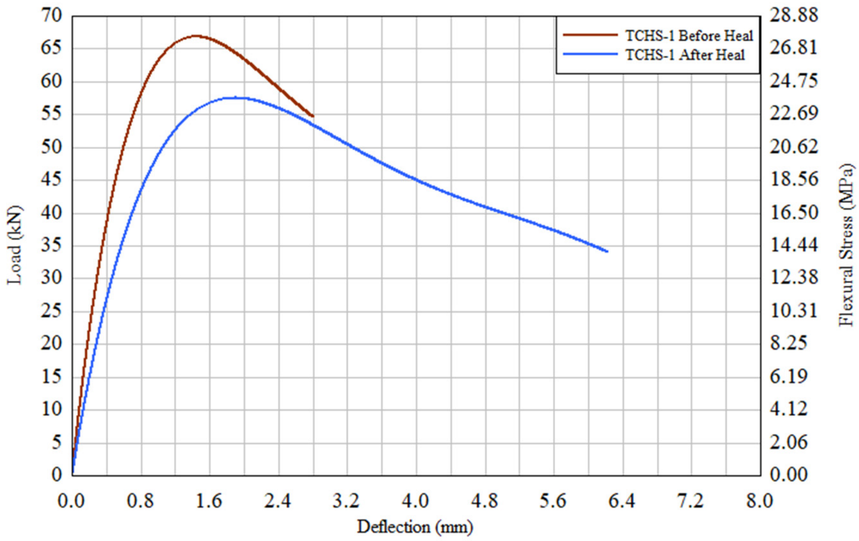

Figure 10. Load−deflection response of Beam "TCHS-1" using the crack-healing solution.

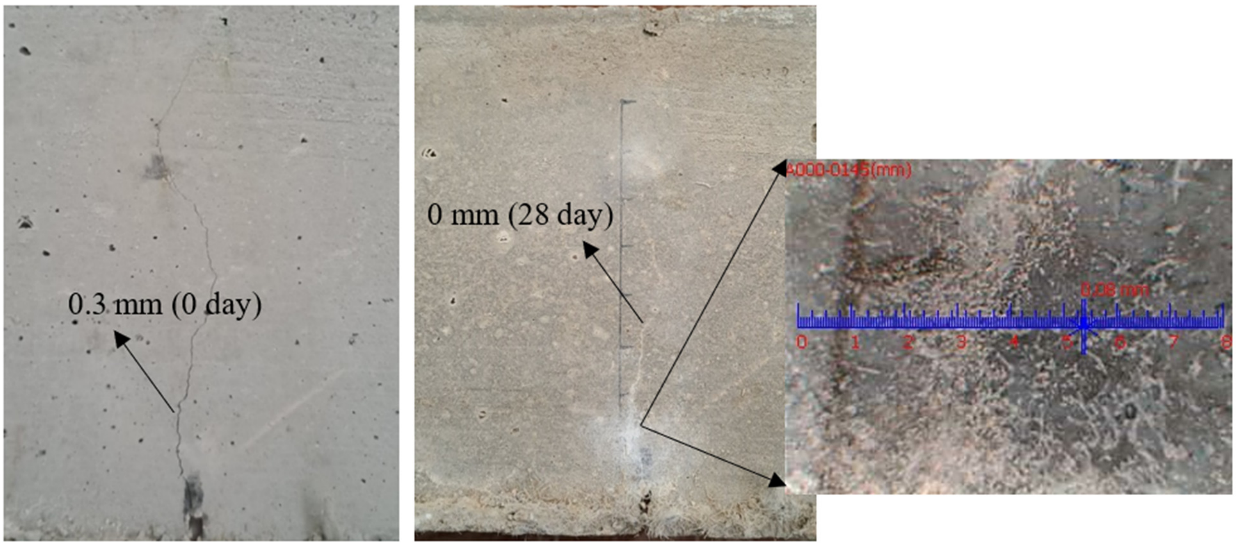

Figure 11. Crack width healed in Beam "TCHS-1" using the crack-healing solution.

3.3. Beam "TCHS-2"

Beam TCHS-2 was also tested until a crack width of 0.3 mm. A peak load of 65.15 kN was attained at about 0.7 mm deflection (refer to Figure 12). The bam was then treated with silica gel plus crack-healing solution and was cured until the designated period. After treatment, the beam was tested again, as shown in Figure 12. The ascending branch was found to have a lesser slope, similar to TCHS-1. This was a sign of stiffness loss after healing. A peak load of 61.2 kN was obtained, which was 6% less than the load before healing. This was better than beam treated with the crack-healing solution only (Beam TCHS-1). This could be because Beam TCHS-2 was kept moist by sprinkling water periodically; thus, there was moisture available during the curing period in the less humid, hot summer season. The descending branch was also similar to the Beam TCHS-1 response. Figure 13 shows the healing effect of the silica gel plus crack-healing solution on the crack that appeared on Beam TCHS-2 with a width of 0.3 mm. The crack was filled with the precipitation of $CaCO_3$ due to *Bacillus subtilis* growth and metabolic activity; however, the same crack opened during re-testing of the beam.

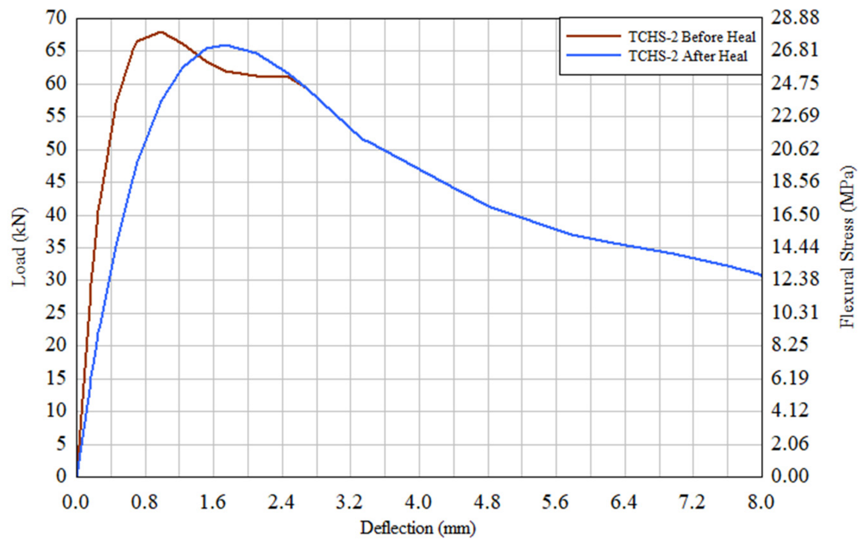

Figure 12. Load–deflection response of Beam "TCHS-2" strengthened using the silica gel plus crack-healing solution.

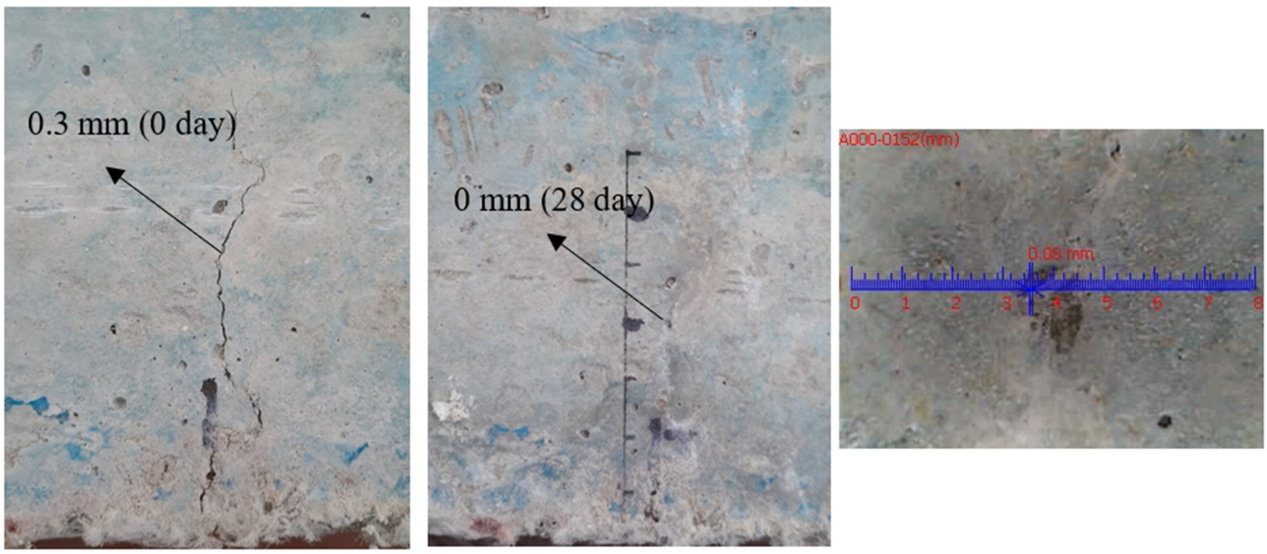

Figure 13. Crack width healed in Beam "TCHS-2" using the silica gel plus crack-healing solution.

3.4. Beam "TCHS-3"

Beam TCHS-3 was also tested up to a crack width of 0.3 mm. The peak load of 63.27 kN was attained at about 1.24 mm deflection (refer to Figure 14). The beam was again tested after the application of the crack-healing solution mixed with cement slurry and was cured until the designated period, as shown in Figure 14. The ascending branch was found to have a lesser slope, similar to TCHS-1 and TCHS-2. A peak load of 55.68 kN was obtained, which was 12% less than the load before healing. This was lower than Beams TCHS-1 and TCHS-2. This could be because Beam TCHS-3 was treated with cement slurry, which blocked the air entrainment into the crack for the necessary metabolic activity of *Bacillus subtilis* mixed as the crack-healing solution. The surface was kept moist by sprinkling water periodically; however, it was not substantially significant in this case. The descending branch was also similar to the response of Beams TCHS-1 and TCHS-2.

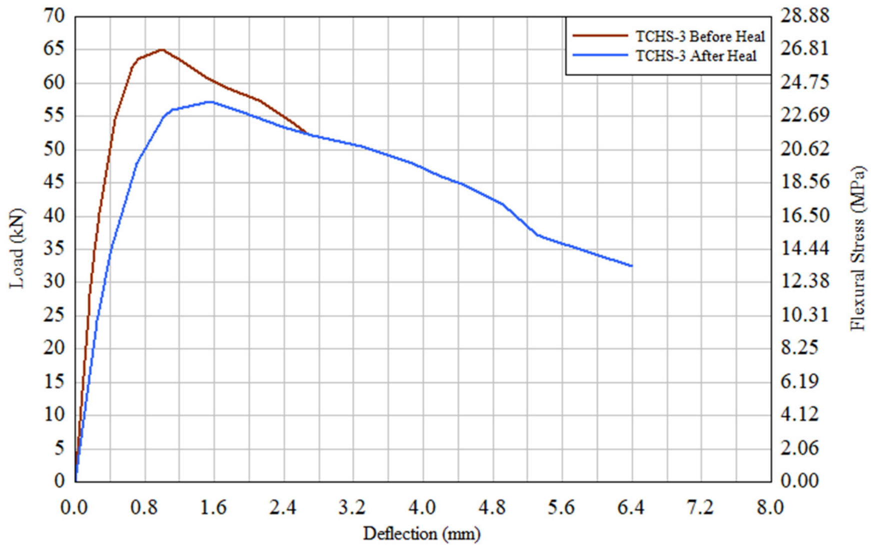

Figure 14. Load−deflection response of Beam "TCHS-3" strengthened using the bacteria cement slurry.

3.5. Beam "TEIM"

The Beam TEIM was also tested up to a crack width of 0.3 mm. The peak load of 68.15 kN was attained at about 1.58 mm deflection (refer to Figure 15). The beam was treated with the application of epoxy injection and cured until the designated period. After healing, the beam was tested again, as shown in Figure 15. The ascending branch was found to have a lesser slope, similar to the beams strengthened by *Bacillus subtilis* in Beams TCHS-1 to TCHS-3. This is a sign that loss in stiffness was inevitable and the crack healing technique seemed to have no impact on the outcome. Additionally, the crack width of 0.3 mm was large enough to bring the beam into the non-linear zone; therefore, it was not possible to achieve complete recovery of stiffness after healing. A peak load of 60.47 kN was obtained, which was 11% less than the load before healing. This was similar to the beam treated with the crack-healing solution only (Beam TCHS-1). The reason might be that Beam TEIM tended to display cracks branching out the existing crack that was injected with epoxy, thus causing crack opening and widening at an early stage. The descending branch was also similar to the beam TCHS-1 response.

Table 5 represents a comparison of the loading capacity with respect to the control and loading capacity before the healing of the cracks. It is clear that all beams attained more than 80% of their loading capacity, which shows the significance of healing spray. It is also competitive with the epoxy-injection method commercially used for cracks repair. Thus, the healing spray was very effective at healing the cracks and attaining a loading capacity, which may infer that the beam will be fully functional after healing cracks in the serviceability limit state loading condition.

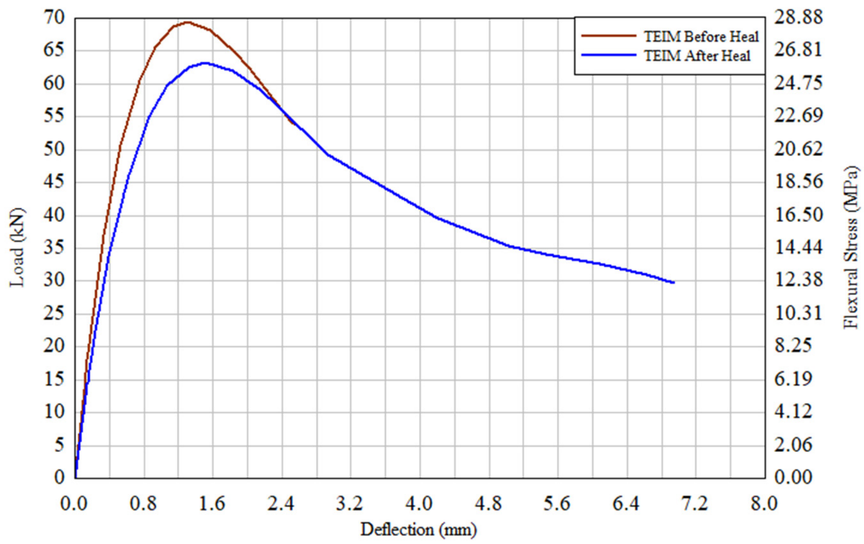

Figure 15. Load−deflection response of Beam "TEIM" strengthened using the epoxy-injection method.

Table 5. Summary of Experimental Program and Results of Beams Before and After Healing.

Beam ID	Details (Application of Repair Technique)	Before Healing (kN)	After Healing (kN)	% Retained Load Capacity w.r.t Control	% Retained Load Capacity w.r.t Loading Capacity before Healing	Crack Width Healed (mm)
Control	Beam without any repair	65	-	-	-	-
TCHS-1	crack-healing solution	68	66	101.54	97.06	0.3
TCHS-2	Silica Gel Plus Crack-healing Solution	66.86	57.51	88.48	84.57	0.3
TCHS-3	Crack-healing Solution mixed with cement slurry	65	57.2	88.00	84.12	-
TEIM	Epoxy-injection Method	69.45	63.2	97.23	92.94	0.3

4. Conclusions

This study focused on the development of a state-of-the-art crack-healing solution and its application on flexural cracks for possible healing, which was measured using a crack-sensing camera. The aim was to regain the member load carrying capacity and achieve the serviceability limit state after healing of the crack. The following conclusions and recommendations can be drawn from this study:

1. A crack-healing technique utilizing bacteria like *Bacillus subtilis* was developed. To ensure sufficient moisture, air, a feeding medium for bacterial metabolic activity, and the resulting precipitation of $CaCO_3$, attention must be given when applying a solution to the crack in the existing structure.
2. The cement constituents are not fatal/harmful to the *Bacillus subtilis*; however, there will be less growth when the bacterial solution is applied with cement slurry paste over the crack for healing.
3. Glucose can be used as a growth supplement for bacteria instead of sodium gluconate.
4. The performance of the crack-healing solution with and without silica gel is comparable to the epoxy-injection method. However, the application of the epoxy-injection method requires more skill and experience and the epoxy-injection method is costlier than the crack-healing solution.

5. Adequate moisture for crack healing through bacteria is a must. An injection system with sealed protection may be used. The crack-healing solution may be injected and remain inside until the cure of the crack.
6. A crack width of 0.3 mm is large enough to bring the beam into the non-linear zone, making complete recovery of stiffness after healing impossible; however, the effectiveness of the crack-healing solution up to this crack width is expected, and it will be more effective in case of cracks of a lesser width at the serviceability limit state. However, further study is recommended to confirm the effectiveness of the crack-healing solution for beams at the serviceability limit state.
7. The crack-healing solution and epoxy-injection method were shown to be efficient in restoring load carrying capacity and reaching the serviceability limit condition; however, there was a little loss in stiffness, which may not be a concern for cracks healed at their initial stage.

Future Research Prospects

1. Sodium gluconate should be investigated to check the amount of precipitation, instead of glucose. Calcium lactate may also be used instead of calcium nitrate when preparing crack-healing solutions.
2. Other bacterial species, e.g., *Bacillus cohnii* and *Bacillus pseudophermus* may be considered to study their effects on healing.

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